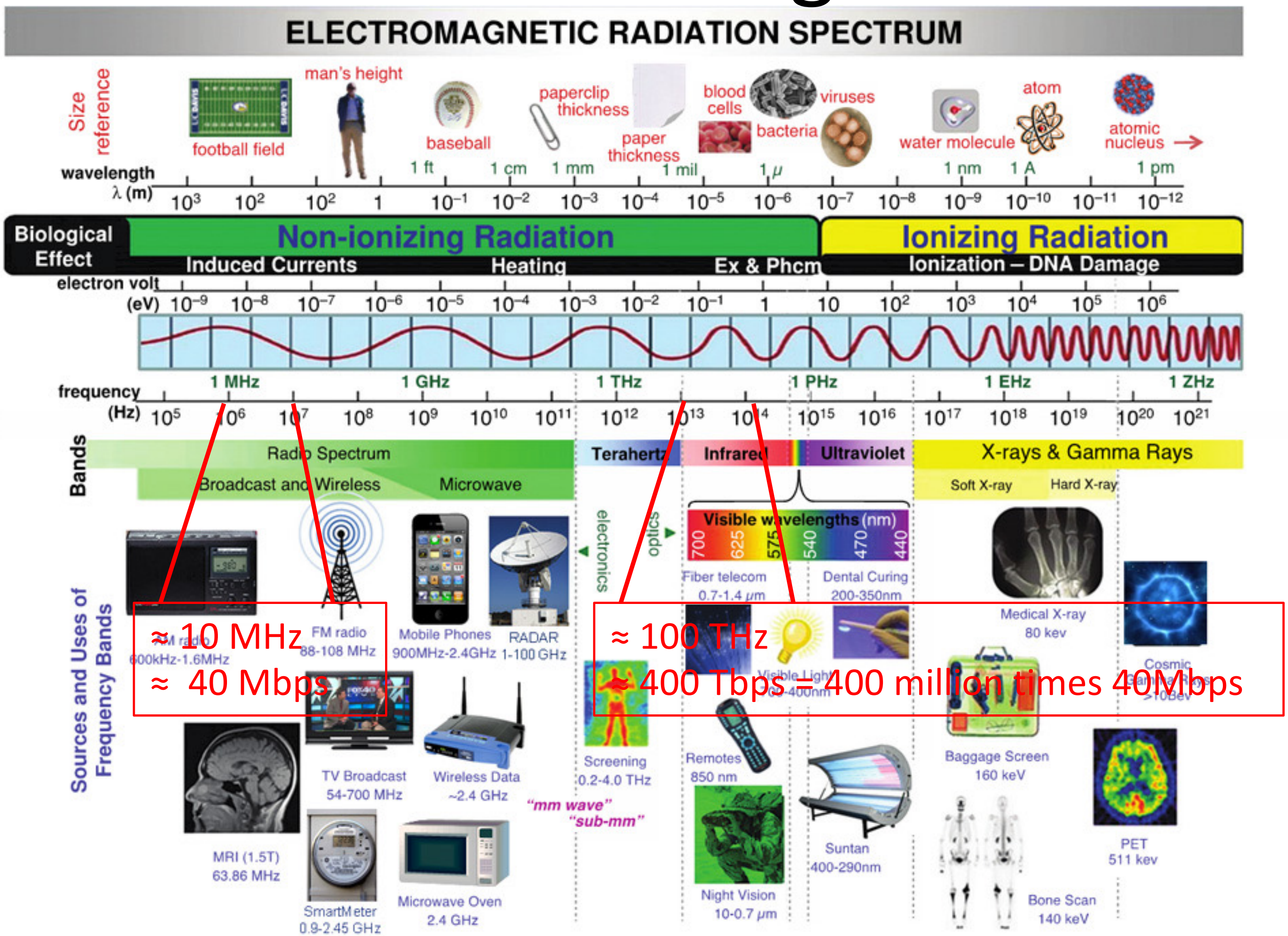
Optical propagation

Optical fibre

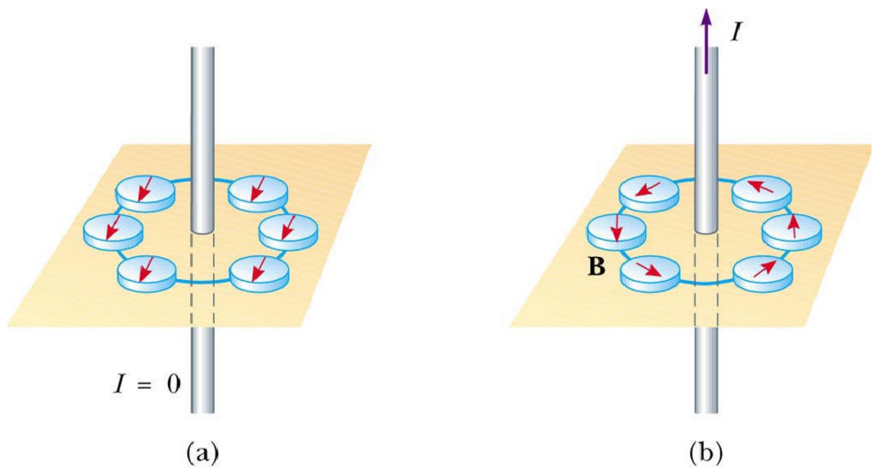
- Uses the total internal reflection phenomenon
- Typical path loss is 0.2 dB/Km
  - Signal can go 150 Km without amplification

What is light?

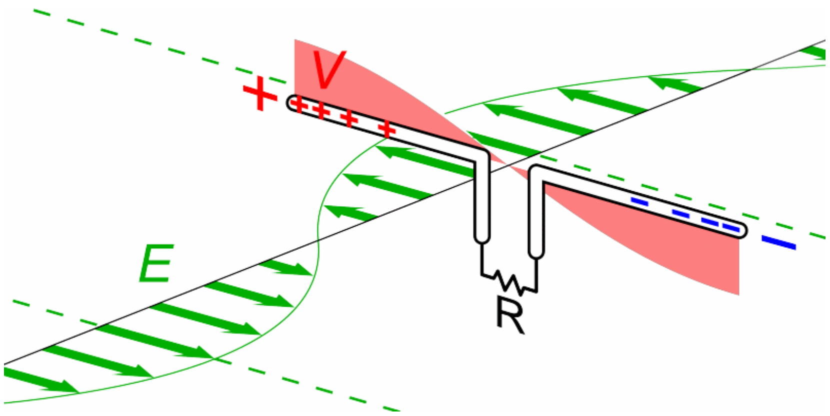


Radiation of copper wires

- A static current on a wire produces a static electro-magnetic field

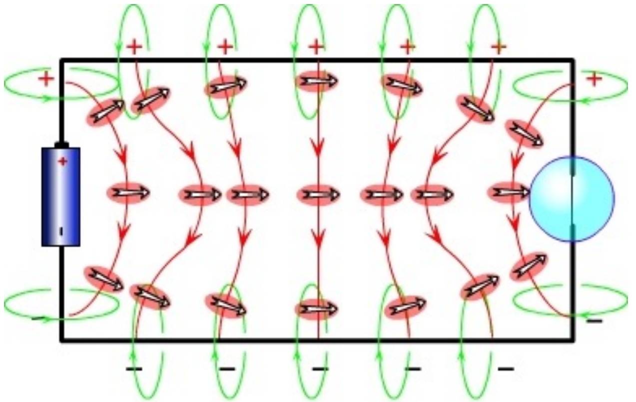


- A variable current on a wire produces a varying electromagnetic field i.e., it radiates energy

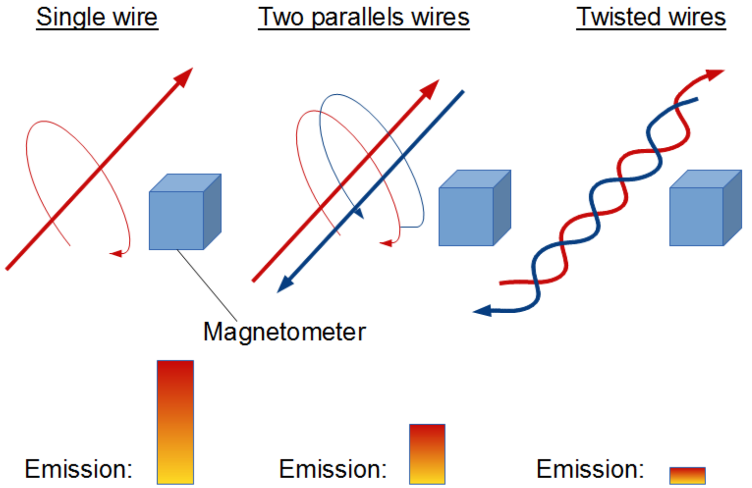


Wires and interference

- A pair of copper wires closed into a circuit will both emit and receive radiation (the duality theorem says that an antenna is as good in transmitting as it is in receiving).

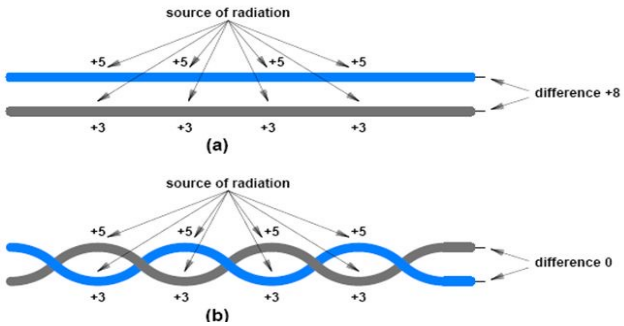


- Since going and returning current have opposite sign they tend to cancel each other interference

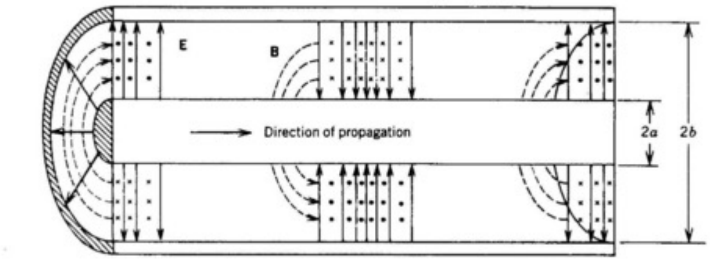


Twisted pair and coaxial

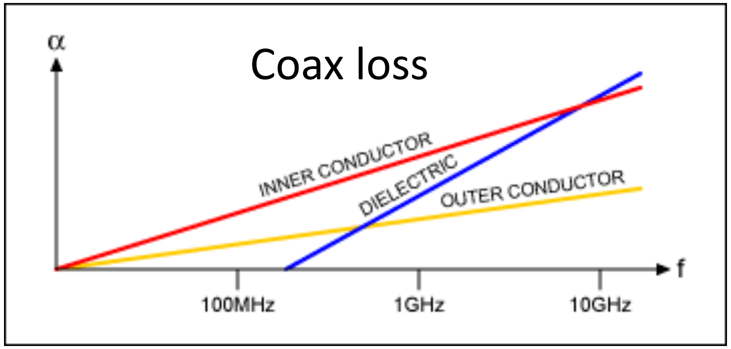
- Twisting the copper helps reducing interference from external sources



- The coaxial uses the Faraday principle by using an external sheet to confine the radiation within the cable



- Signal losses occur in (1) dissipation in the conductor, (2) dissipation in the dielectric and (3) radiation (small).
  - Most loss is in the conductor and at higher frequencies is lower for coax due to the larger conductor size (especially the external one)
  - Dielectric losses are also lower in coax as the inner material has typically lower density



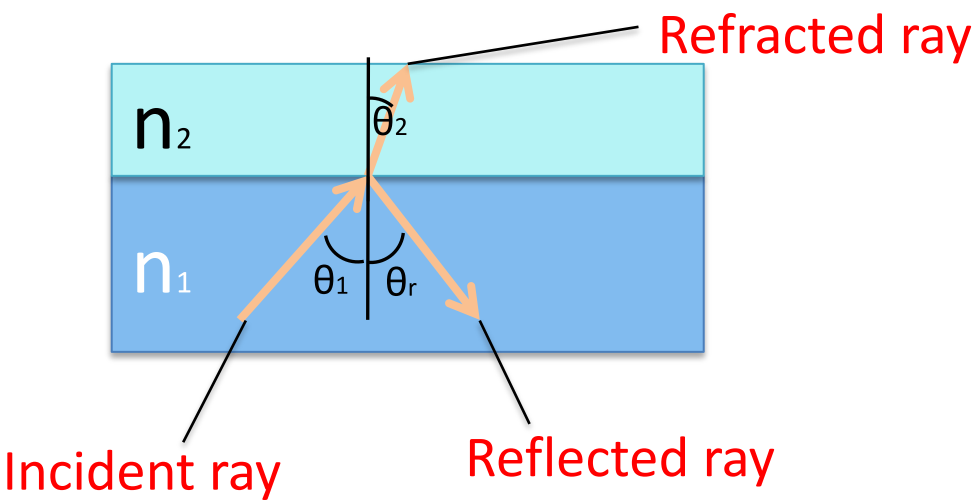
Optical fibre:
Total internal reflection

Consider two materials with different refractive index: $n_{1,}n_{2}$

$$n = \frac{c_0}{c}$$

c_0 → Speed of light in the vacuum

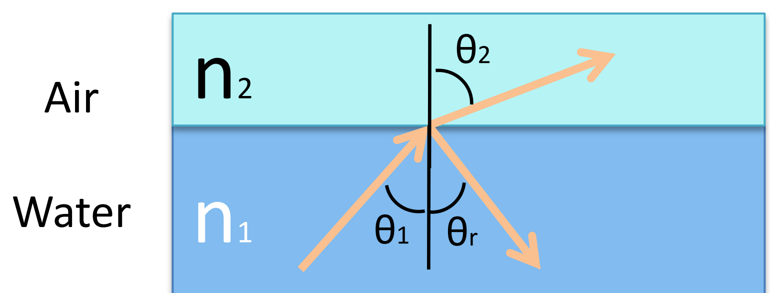
c → Speed of light in the medium considered



Snell's law:

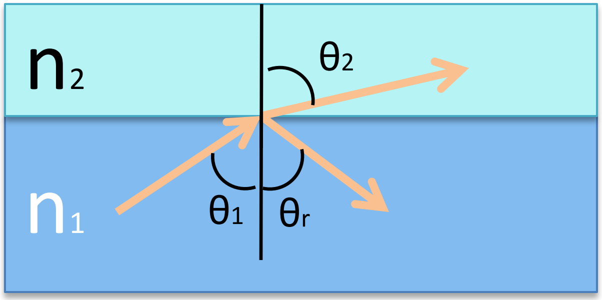
- $\theta_1 = \theta_r$
- $\dfrac{\sin\theta_1}{\sin\theta_2} = \dfrac{n_2}{n_1}$

$$If\; n_1 > n_2 \Rightarrow \theta_2 > \theta_1$$

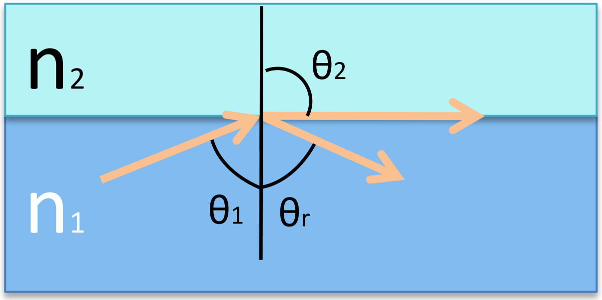


Total internal reflection

Increasing θ_1



θ_2 Increases

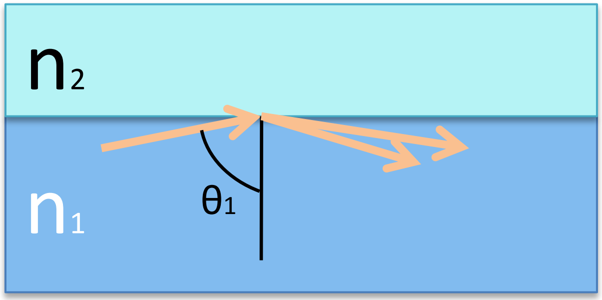


There is a value for $\theta_1 < \frac{\pi}{2}$ for which $\theta_2 = \frac{\pi}{2}$

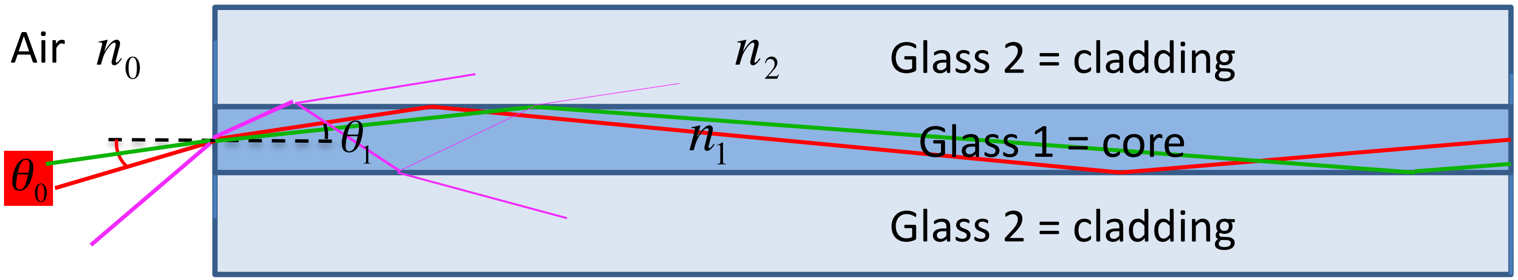
critical angle $\theta_{1-crit} = \sin^{-1}(\frac{n_2}{n_1})$

For $\theta_1 \geq \theta_{1-crit}$ we have total internal reflection
The light remains confined inside n_2!

This is how optical fibre operates

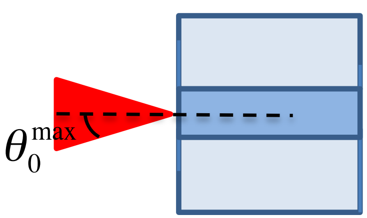


Propagation in optical fibre



This fibre is called step-index, because the index n changes suddenly between cladding and core.

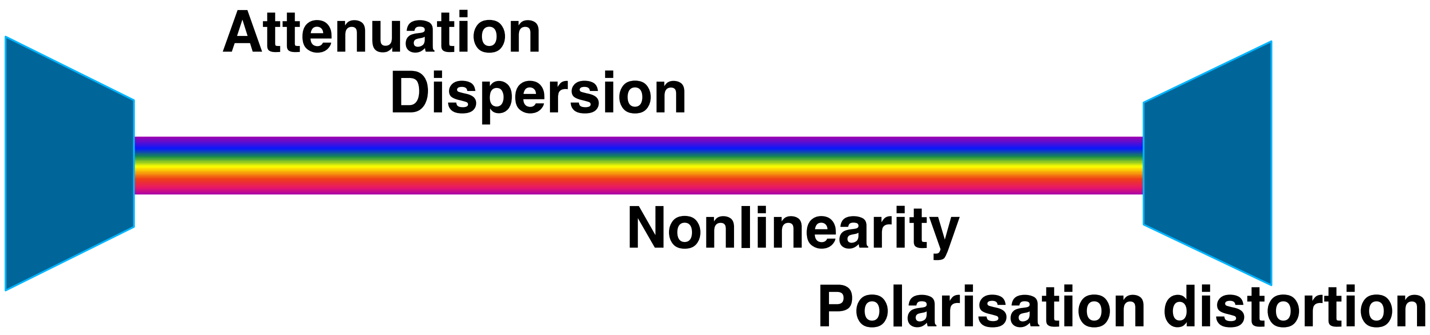
- Rays incident at an angle $\leq \theta_0^{max}$ will propagate in the fibre through total internal reflection
- Rays incident at anangle $> \theta_0^{max}$ will loose power while propagating through the refracted ray



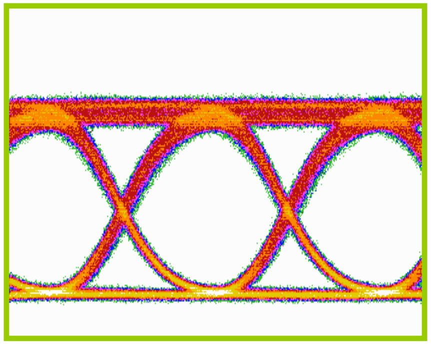
All rays with $\theta_0 \leq \theta_0^{max}$ form a "Cone of acceptance"

$$\theta_0^{max} = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$$

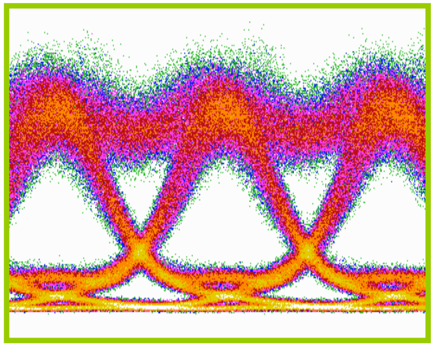
FIBRE FUNDAMENTALS



The aim is to transmit signals with the minimum distortion



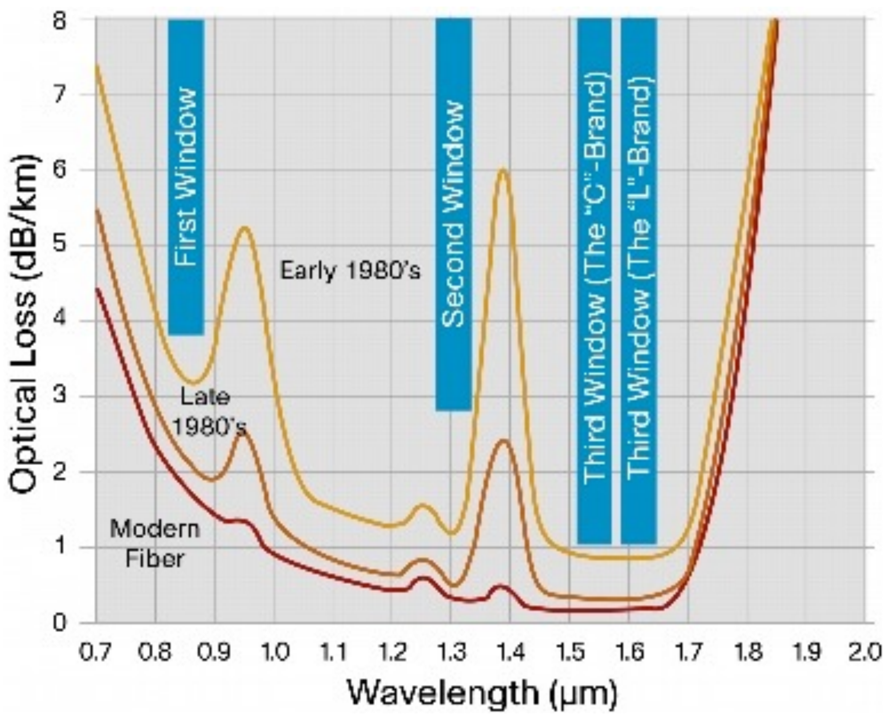
Transmitted Data Waveform



Waveform After 1000 Km

Path loss in fibre

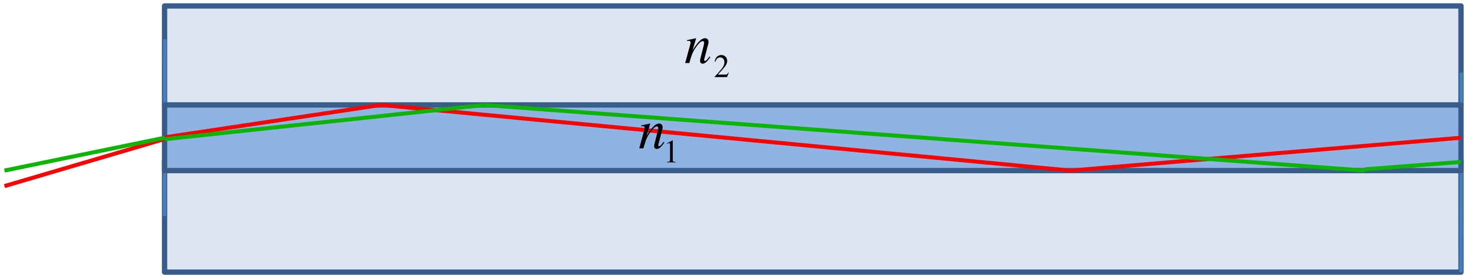
- The amount of power lost during propagation depends on the frequency (or wavelength) used for transmission.
- The smallest loss is at a wavelength of 1.55 μm, and is 0.2 dB/Km



Dispersion in fibre

- Dispersion in fibre is due to the fact that the refractive index n is not constant, but its value depends on the frequency of the signal.
- The dispersion coefficient D It is measured in $\dfrac{ps}{nm \cdot km}$
- There are three types of dispersion:
  - Modal dispersion: because different modes propagate at different speed (only occurs in multi-mode fibre)
  - Chromatic dispersion: because different frequencies within a single mode propagate at different speed
  - Polarization mode dispersion: because different spatial polarization can propagate at different speed

Modal dispersion in optical fibre



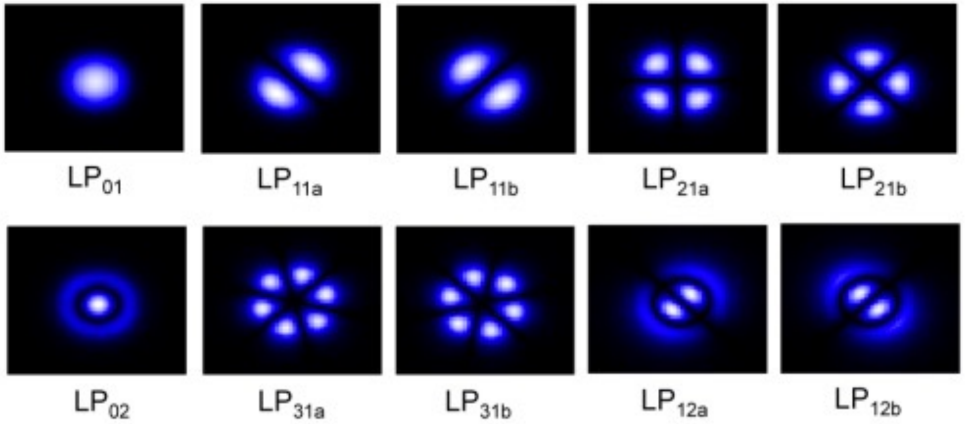
- The green and red rays are called modes of propagation in the fiber.

- Since red is reflected at a narrower angle than green, it will travel a longer distance for a same amount of fibre.

- Since green and red travel at the same speed, red will arrive at destination later than green.

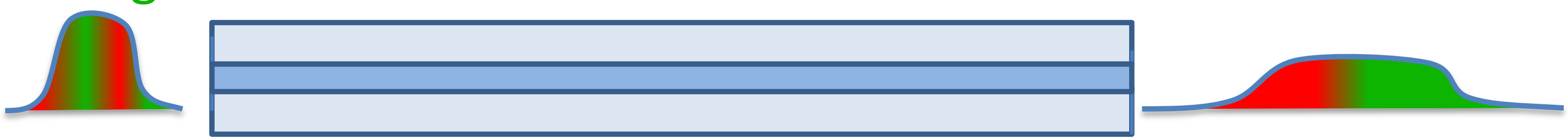
<u>More precisely, modes are solutions of the Maxwell equations applied to optical fibres.</u>

Visualising the different modes (in special coordinates x,y)



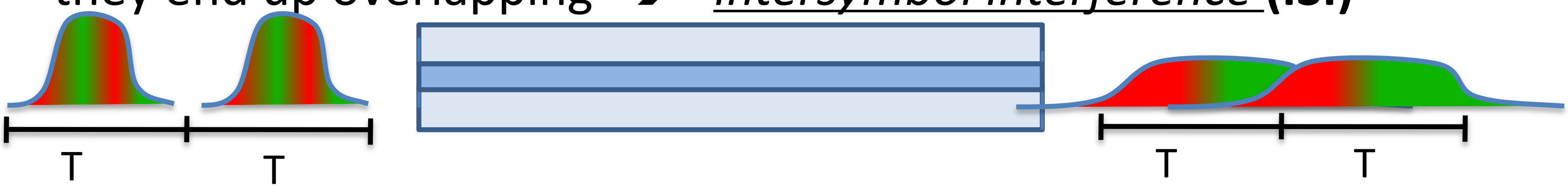
Impairments caused by modal dispersion

- If I transmit a pulse it will be composed of a number of different modes, <u>for simplicity here are indicated with two colors</u>, red and green



because red is slower than green the pulse spreads, and its peak power decreases

- In a communication channel where I transmit a series of pulses, they end up overlapping → <u>*intersymbol interference*</u> **(ISI)**

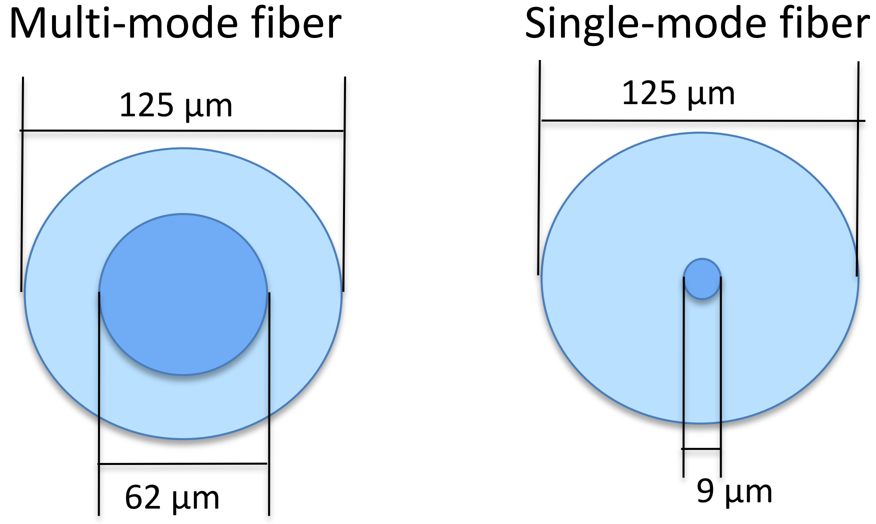


Single-mode vs. multi-mode

- A multi-mode fibre has a larger core, which allows multiple modes to coexist at the frequencies used for optical communication

- A single-mode fibre has a smaller core, which only allows one propagation mode.

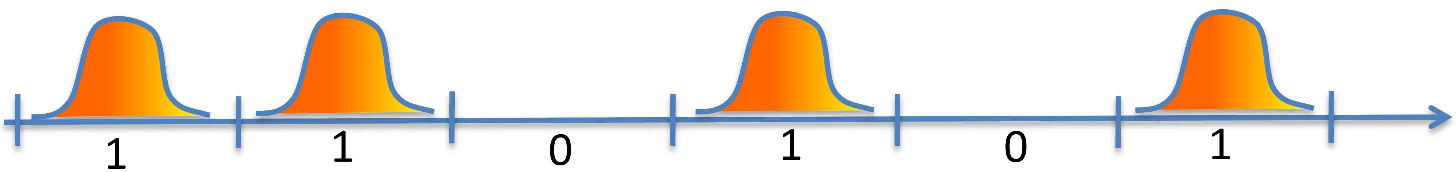
- **<u>Modal dispersion is simply eliminated by using single-mode fibre!!</u>**



Single-mode fiber is the most used in telecommunications

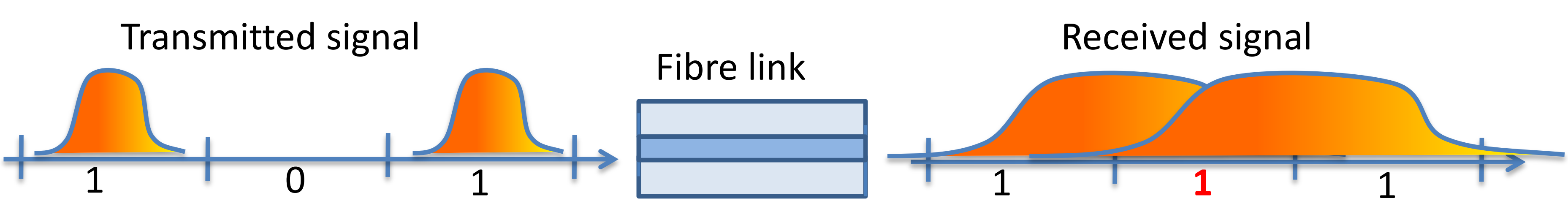
Chromatic dispersion problem

- Optical communications is achieved by transmitting pulses



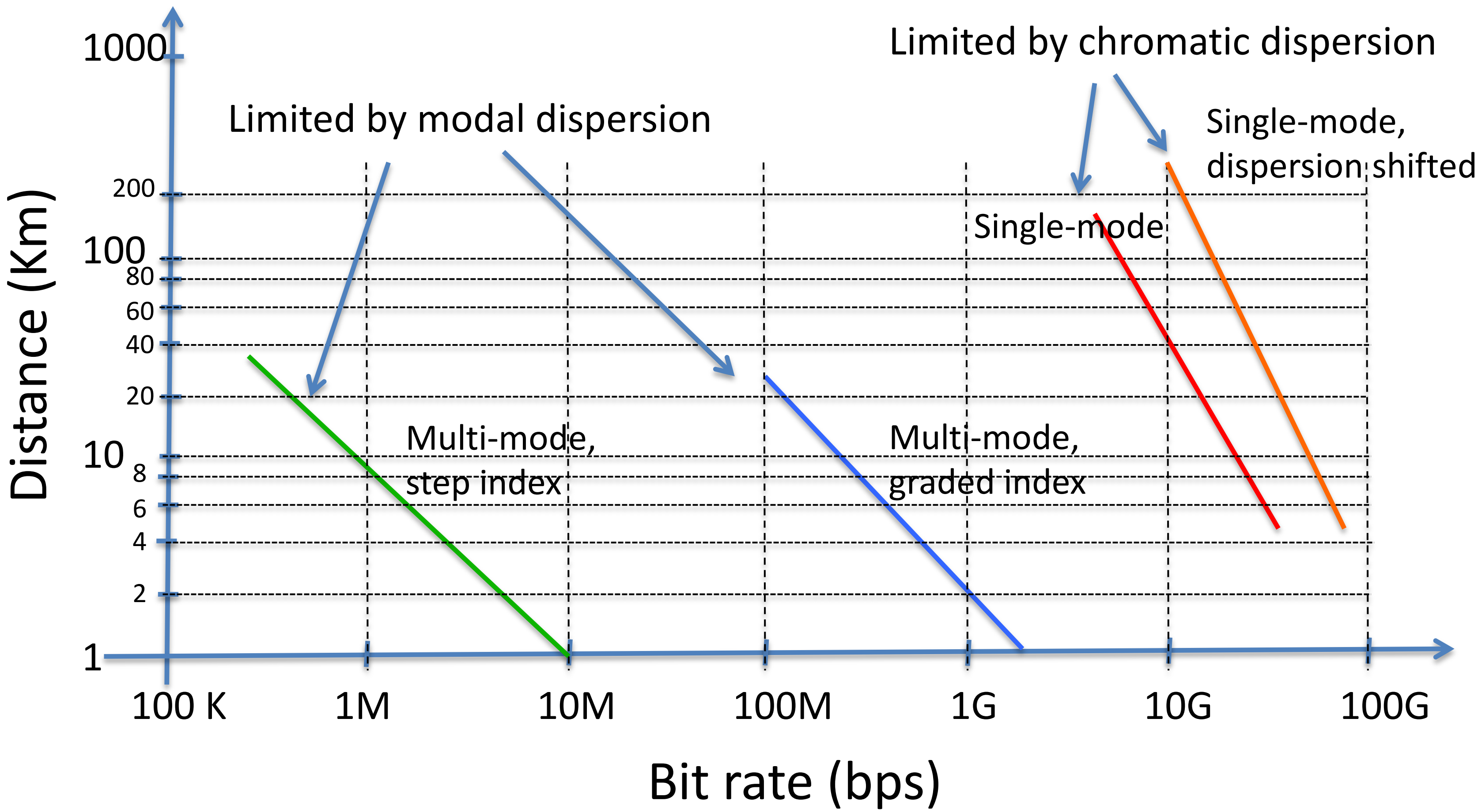
- Each pulse has a finite spectral width (it's made of a number of adjacent frequencies)

- If lower frequencies travel slower than higher ones, the pulse spreads, causing transmission errors



Modal and chromatic dispersion

- Modal dispersion ***only*** occurs in multi-mode fibres
- The amount of dispersion depends both on the data rate, and on the length of fibre where the signal propagates

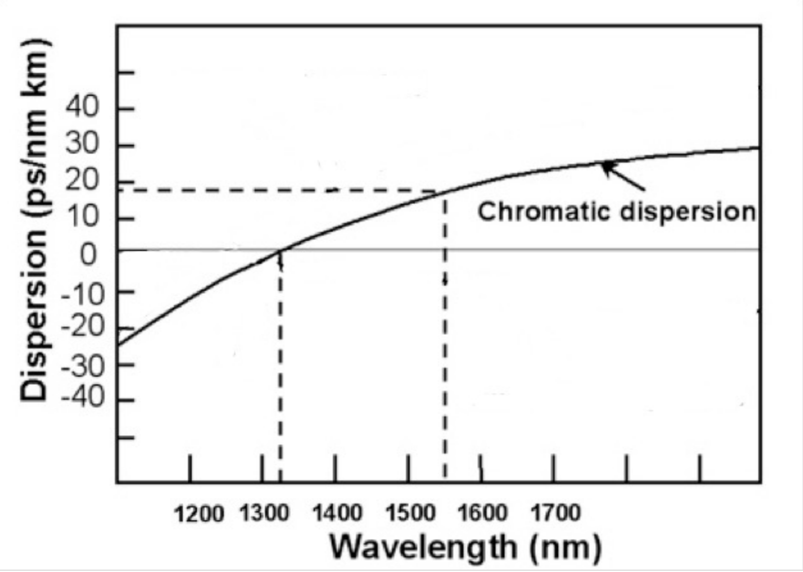


Modal and chromatic dispersion

- Modal dispersion has the biggest effects:
  - **This is why telecoms systems use mostly single mode fibres!**

- Chromatic dispersion is the second most important cause:
  - Due to the fact that different frequency components of a pulse travel at different speed
  - Dispersion is measured in Picoseconds per nanometer of bandwidth per kilometer

    ➔ How many nanoseconds does a pulse broadens, if its bandwidth is 1 nanometer and it has travelled for 1 Km

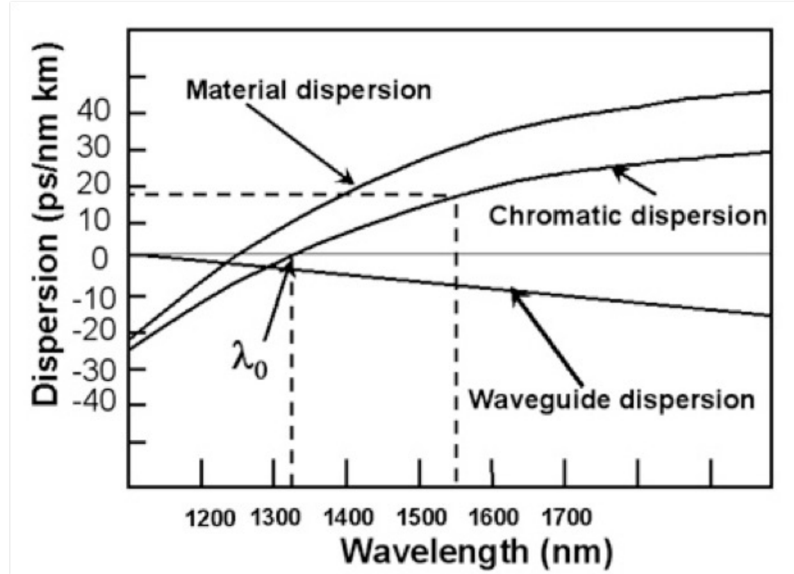


- The lowest loss wavelengths of 1.55 µm has 17ps/nm/km dispersion

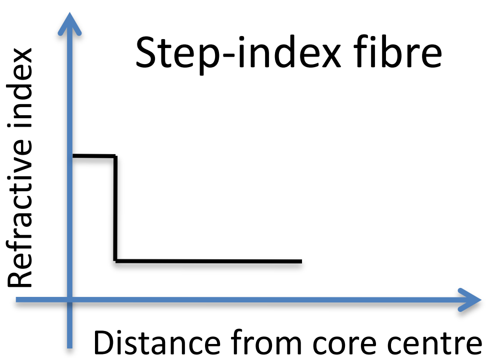
- While at 1.3 µm dispersion is almost null

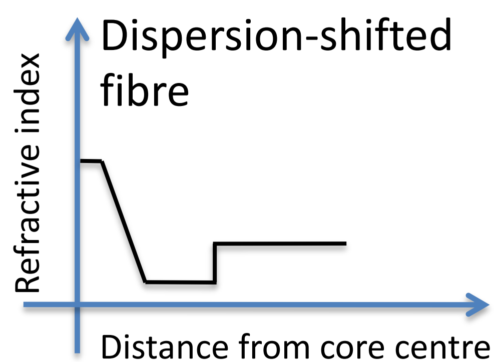
Dispersion shifted fibre

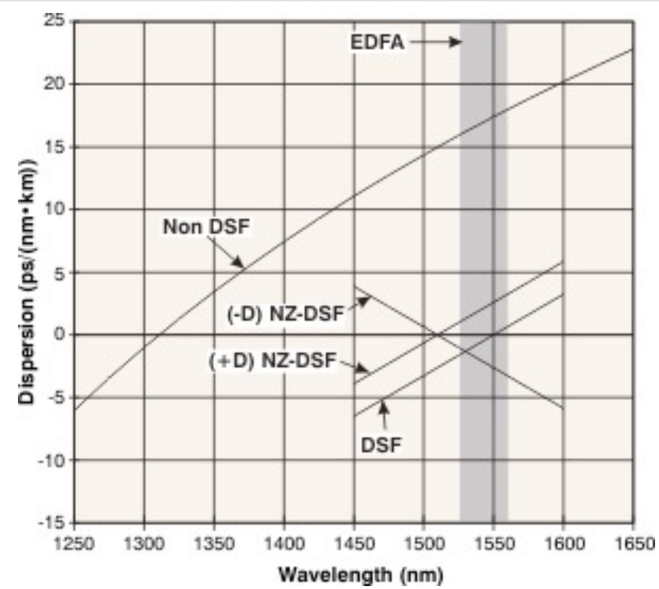
- Dispersion in fibre is due to:
  - the material (cannot be changed)
  - the shape of the waveguide, i.e. the shape of the fibre cross section (this can be changed, like we did for the graded-index fibre)



- I can modify the dispersion by changing the distribution of the refractive index



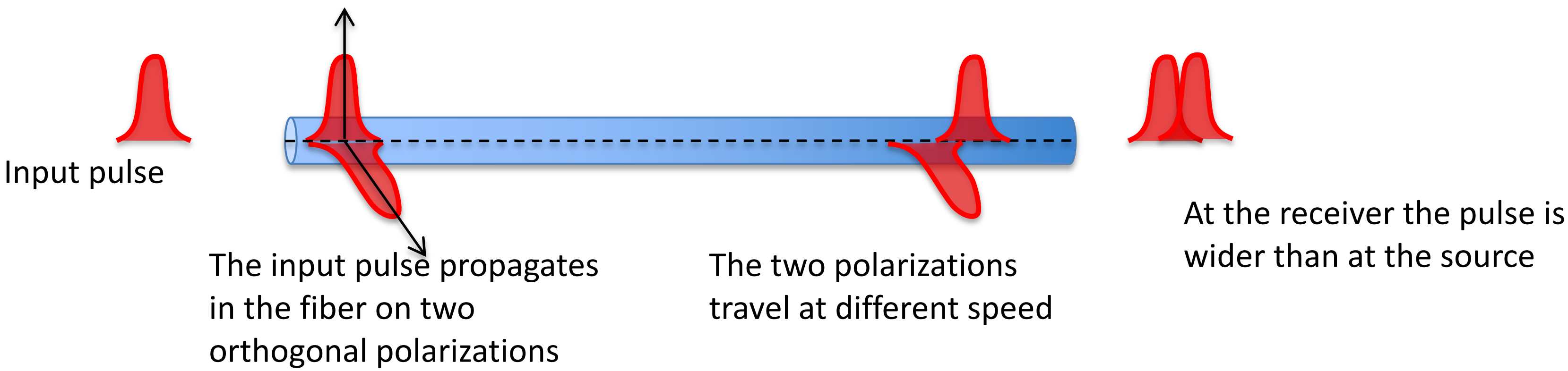




Polarization-mode dispersion (PMD)

- The electric field in a single mode fibre propagates with two orthogonal polarization
- Because of imperfect production techniques, the fiber is not completely symmetrical

  ➔ The two orthogonal components of the electric field have different propagation characteristics



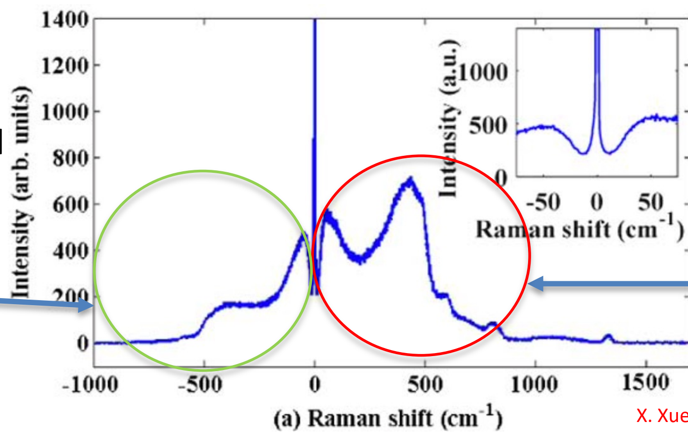
- PMD is less severe than chromatic dispersion: about 0.5 ps/km

Non-linear effects

- Nonlinearity implies that the transfer function of the fiber depends on the signal being transmitted. Their effects increase with the transmitted power.

- Raman scattering:
  - Light interacts with phonons, generating photons with different frequency from the incoming signal.
  - Spontaneous → random frequency and phase = noise
  - Stimulated → same frequency and phase = amplification (there are Raman amplifiers that make use of this effect)

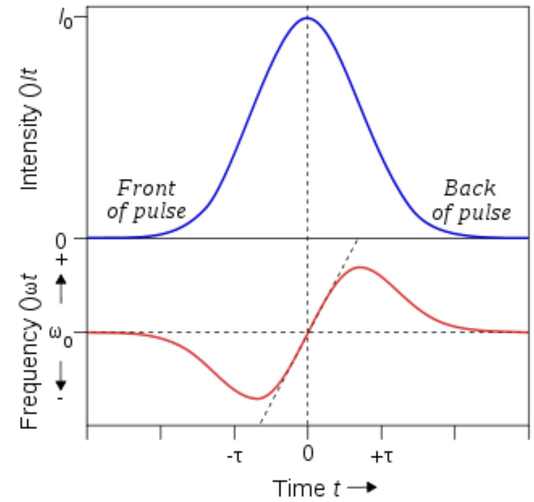
Anti-Stokes lines:
existing signal + phonon = new signal
New signal has shorter wavelength (higher frequency) than incoming signal



Stokes lines:
existing signal – phonon = new signal
New signal has longer wavelength (lower frequency) than incoming signal

X. Xue et al. "Low-frequency shift Raman spectroscopy using atomic filters," Opt. Lett. 41, 5397-5400 (2016)

Non-linear effects



- Self-phase modulation (SPM):
  - since the refractive index depends on the intensity of the traveling light, an amplitude-modulated signal sees different values of n, and is subject to a different propagation constant

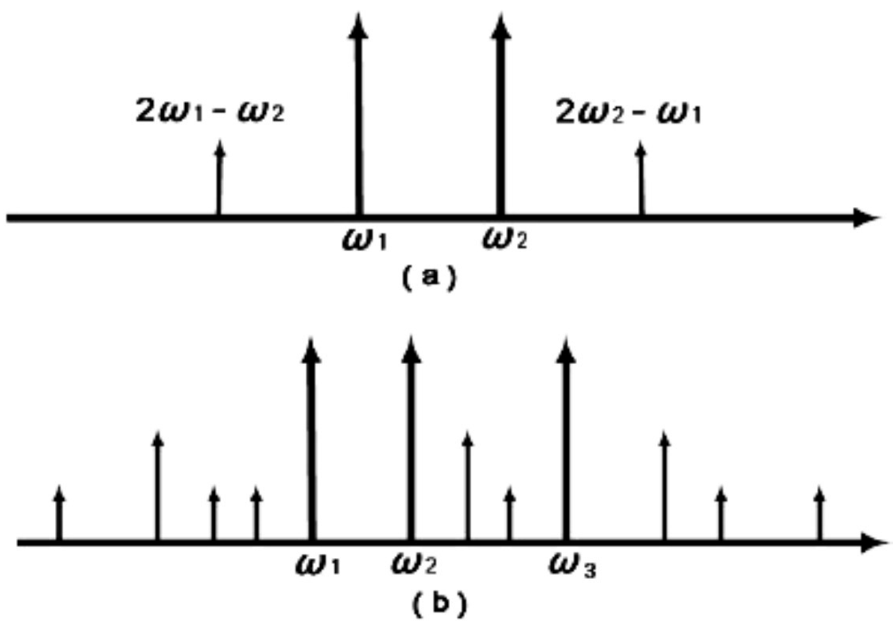
- Cross-phase modulation (CPM): if there are multiple wavelengths in a fiber (WDM), the modulation of other wavelengths produce changes in the refractive index that affects (re-modulate) the signal

Same concept but the effect is across different signals

Both SPM and CPM produce a broadening of the pulse, so create additional dispersion and are more problematic at higher rates

Non-linear effects

- Four-wave mixing (FWM):
  - the refractive index nonlinearity also generates new frequencies
  - Based on 3rd order nonlinearity, produces signals whose frequency is the sum or difference of input signals (i.e., $\omega = \omega_i \pm \omega_j \pm \omega_k$)
  - This can generate noise in WDM systems. It does not depend on data rate, but it is worse when the wavelength spacing is small



Tyagi, Lalit & Kumar, Arvind & Joshi, Tripuresh. (2012). Performance Analysis of Four Wave Mixing Based Wavelength Conversion in Commercial Optical Fibers. IJSRP. 2. 2250-3153.

Shannon capacity and nonlinearity

$$C = B \cdot log_2(1 + \frac{S}{N})$$

The capacity of a communication channel is proportional to the Bandwidth of the signal and to the $\log_2$ of the signal to noise ratio

→ In linear regime the higher the signal power, the higher the capacity

However we have seen that nonlinearity introduces noise that is proportional to the signal power